

A Community Terrain-Following Ocean Modeling System (ROMS/TOMS)

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Award Number: N00014-08-1-0542

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LONG-TERM GOALS

The long-term technical goal is to design, develop and test the next generation, primitive equation, ocean model for high-resolution scientific (ROMS: Regional Ocean Modeling System) and operational (TOMS: Terrain-following Ocean Modeling System) applications. This project will improve the ocean modeling capabilities of the U.S. Navy for relocatable, coastal, coupled atmosphere-ocean forecasting applications. It will also benefit the ocean modeling community at large by providing the current state-of-the-art knowledge in physics, numerical schemes, and computational technology.

OBJECTIVES

The main objective is to produce a tested expert ocean modeling framework for scientific and operational applications over a wide range of spatial (coastal to basin) and temporal (days to seasons) scales. The primary focus is to implement the most robust set of options and algorithms for relocatable coastal forecasting systems nested within basin-scale operational models for the Navy. The system includes some of the analysis and prediction tools that are available in Numerical Weather Prediction (NWP), like 4-Dimensional Variational (4DVar) data assimilation, ensemble prediction, adaptive sampling, and circulation stability and sensitivity analysis.

APPROACH

The structure of TOMS is based on ROMS because of its accurate and efficient numerical algorithms, tangent linear and adjoint models, variational data assimilation, modular coding and explicit parallel structure conformal to modern computer architectures (both cache-coherent shared-memory and distributed cluster technologies). Currently, both ROMS and TOMS are identical and continue improving and evolving. ROMS remains as the scientific community model while TOMS becomes the operational community model.

ROMS/TOMS is a three-dimensional, free-surface, terrain-following ocean model that solves the Reynolds-averaged Navier-Stokes equations using the hydrostatic vertical momentum balance and Boussinesq approximation (Haidvogel *et al.* 2000, 2008; Shchepetkin and McWilliams, 2005). The governing dynamical equations are discretized on a vertical coordinate that depend on the local water depth. The horizontal coordinates are orthogonal and curvilinear allowing Cartesian, spherical, and polar spatial discretization on an Arakawa C-grid. Its dynamical kernel includes accurate and efficient algorithms for time-stepping, advection, pressure gradient (Shchepetkin and McWilliams 2003, 2005), several subgrid-scale parameterizations (Durski *et al.*, 2004; Warner *et al.*, 2005) to represent small-

Report Documentation Page			Form Approved OMB No. 0704-0188		
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1. REPORT DATE 30 SEP 2008		2. REPORT TYPE Annual		3. DATES COVERED 00-00-2008 to 00-00-2008	
4. TITLE AND SUBTITLE A Community Terrain-Following Ocean Modeling System (ROMS/TOMS)			5a. CONTRACT NUMBER		
			5b. GRANT NUMBER		
			5c. PROGRAM ELEMENT NUMBER		
6. AUTHOR(S)			5d. PROJECT NUMBER		
			5e. TASK NUMBER		
			5f. WORK UNIT NUMBER		
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Rutgers University, Institute of Marine and Coastal Sciences, 71 Dudley Road, New Brunswick, NJ, 08901-8521			8. PERFORMING ORGANIZATION REPORT NUMBER		
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)			10. SPONSOR/MONITOR'S ACRONYM(S)		
			11. SPONSOR/MONITOR'S REPORT NUMBER(S)		
12. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release; distribution unlimited					
13. SUPPLEMENTARY NOTES code 1 only					
14. ABSTRACT The long-term technical goal is to design, develop and test the next generation, primitive equation, ocean model for high-resolution scientific (ROMS: Regional Ocean Modeling System) and operational (TOMS: Terrain-following Ocean Modeling System) applications. This project will improve the ocean modeling capabilities of the U.S. Navy for relocatable, coastal, coupled atmosphere-ocean forecasting applications. It will also benefit the ocean modeling community at large by providing the current state-of-the-art knowledge in physics, numerical schemes, and computational technology.					
15. SUBJECT TERMS					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT Same as Report (SAR)	18. NUMBER OF PAGES 7	19a. NAME OF RESPONSIBLE PERSON
a. REPORT unclassified	b. ABSTRACT unclassified	c. THIS PAGE unclassified			

scale turbulent processes at the dissipation level, and various bottom boundary layer formulations to determine the stress exerted on the flow by the bottom.

Several adjoint-based algorithms exist to explore the factors that limit the predictability of the circulation in regional applications for a variety of dynamical regimes (Moore et al., 2004). These algorithms use the ideas of Generalized Stability Theory (GST) in order to identify the most unstable directions of state-space in which errors and uncertainties are likely to grow. The resulting singular vectors can be used to construct ensembles of forecasts by perturbing initial and boundary conditions (optimal perturbations) and/or perturbing surface forcing (stochastic optimals). Perturbing the system along the most unstable directions to the state-space yields information about the first (ensemble mean) and second (ensemble spread) moments of the probability density function. Given an appropriate forecast skill measure, the circulation is predictable if low spread and unpredictable if large spread.

There are several adjoint-based variational data assimilation algorithms available in ROMS. For cases in which the dynamics are imposed as a strong constraint (*i.e.* no model error assumed), there is an incremental 4DVar (Powell et al., 2007a, b) driver (IS4DVAR) similar to that used operationally at some numerical weather prediction centers. In the case where errors are admitted in the model, there is an indirect representer-based weak constraint 4DVar (Di Lorenzo et al., 2007; Muccino et al., 2007) driver (W4DVAR) and a weak constraint Physical Space Analysis System (W4DPSAS) driver.

ROMS is a very modern and modular code written on F90/F95. It uses C-preprocessing to activate the various physical and numerical options. The parallel framework is coarse-grained with both shared-memory (OpenMP) and distributed-memory (MPI) paradigms coexisting in the same code. Because of its construction, the parallelization of the adjoint is only available for MPI. Several coding standards have been established to facilitate model readability, maintenance, and portability. All the state model variables are dynamically allocated and passed as arguments to the computational routines via dereferenced pointer structures. All private arrays are automatic; their size is determined when the procedure is entered. This code structure facilitates computations over nested grids. There are three types of nesting capabilities in ROMS: (i) *refinement* grids which provide increased resolution (3:1 or 5:1) in a specific region; (ii) *mosaics* which connect several grids along their edges, and (iii) *composite* grids which allow overlap regions of aligned and non-aligned grids.

WORK COMPLETED

A continuous real-time prediction exercise was carried out from January 1 to April 19, 2008 in the Philippine Archipelago to support the *Joint* and *First IOP* cruises. The forecasts were issued daily and posted at <http://www.myroms.org/philex>. Each prediction cycle was run for 9 days (4-day hindcast and 5-day forecast). Only the 5-day forecasts are issued at 6-hour intervals. The model was forced with 3-hours NOGAPS forecasts winds and fluxes (half-degree resolution). The lateral boundary conditions were from HyCOM 1/12 degree global run with NCODA and tidal forcing was taken from the global OTPS model. None of the forecasts included data assimilation because the observations were not available in real-time. However, hindcast data assimilation runs are carried out as field measurements become available. This is part of an ONR-supported direct research initiative to study the meso- and submesoscale dynamics in Straits of the Philippine Archipelago (denoted as PhilEx).

We held two very successful workshops at University of California the first week in October 2007. The annual ROMS workshop was held October 1st and 2nd. The agenda and presentations can be found

at http://www.myroms.org/?page=ROMS_2007_agenda. The quality and diversity of applications were exceptional this year. This is the first time that several training sessions (October 3rd) were offered to present various ROMS capabilities and usage including: (i) Subversion tutorial, (ii) grid generation tools, (iii) parallelism tutorial, (iv) model coupling, and (v) how to set up a realistic application. These tutorials were recorded and posted on the website so the ROMS user community, present and future, can benefit from this type of technical training. In addition, we held the Community Sediment Transport Modeling (CSTM) workshop on October 4th and 5th. The main objective was to review the status of the sediment model algorithms and decide which additional sediment processes should be represented in the model. The issues of model coupling using the ESMF and/or MCT libraries were discussed and evaluated. The CSTM project is funded by NOPP in collaboration with C. Sherwood (USGS), R. Geyer (WHOI), T. Keen (NRL), and another 28 partners from several universities and government agencies.

RESULTS

The latest version of the ROMS svn repository, revision 166, was frozen and tagged as ROMS 3.1 on March 18, 2008. This version is quite stable and included several improvements to the 4DVar data assimilation algorithms, a generic ESMF and MCT model coupling interface, an infrastructure for multi-grid nesting (composite, mosaic, and refined), least-squares detiding capabilities, and the restructuring of the sediment model into several process-based (stratigraphy, bedload, deposition, resuspension, erosion, vertical settling, etc.) components.

Figure 1 shows an example of the detiding capabilities within ROMS for the Philippine Archipelago application (5km grid). The detiding algorithm (inside ROMS) uses a least squares fit on the predicted state variables (usually free surface, 2D and 3D momentum) to extract the harmonic constituents of the tides. Due to the nonlinear interactions between tidal constituents, a long simulation is required for this type of harmonic analysis. In the Philippine Archipelago (Fig. 1), almost a year long record is needed to resolve and extract the diurnal (K1, P1, O1, and Q1) and semi-diurnal (K2, S2, M2, and N2) components. The resulting elevation amplitudes, per component, are in good agreement with those predicted by OTPS (not shown) except in the Archipelago's interior (between Panay, Negros and Cebu islands). ROMS over estimates the elevation amplitudes there because of coarse grid resolution and bathymetry representation. The 5km grid resolution does not represent the inter-island passages very well. However, the elevation amplitude predictions are much smaller and closer to OTPS in the 2km ROMS grid harmonic analysis. With respect to the phase, the tidal decomposition shows a much smaller structure than those predicted by OTPS. This can be explained in terms of the baroclinic tide's effects on the sea-surface elevation.

A lot of work has been done in WikiROMS (<https://www.myroms.org/wiki>) to improve the documentation. The underlying software of WikiROMS was updated and a new extension was added to allow real TeX syntax for mathematical equations. The resulting equations are rendered in higher quality when compared to default version. This has facilitated the addition of much of the missing technical information about ROMS.

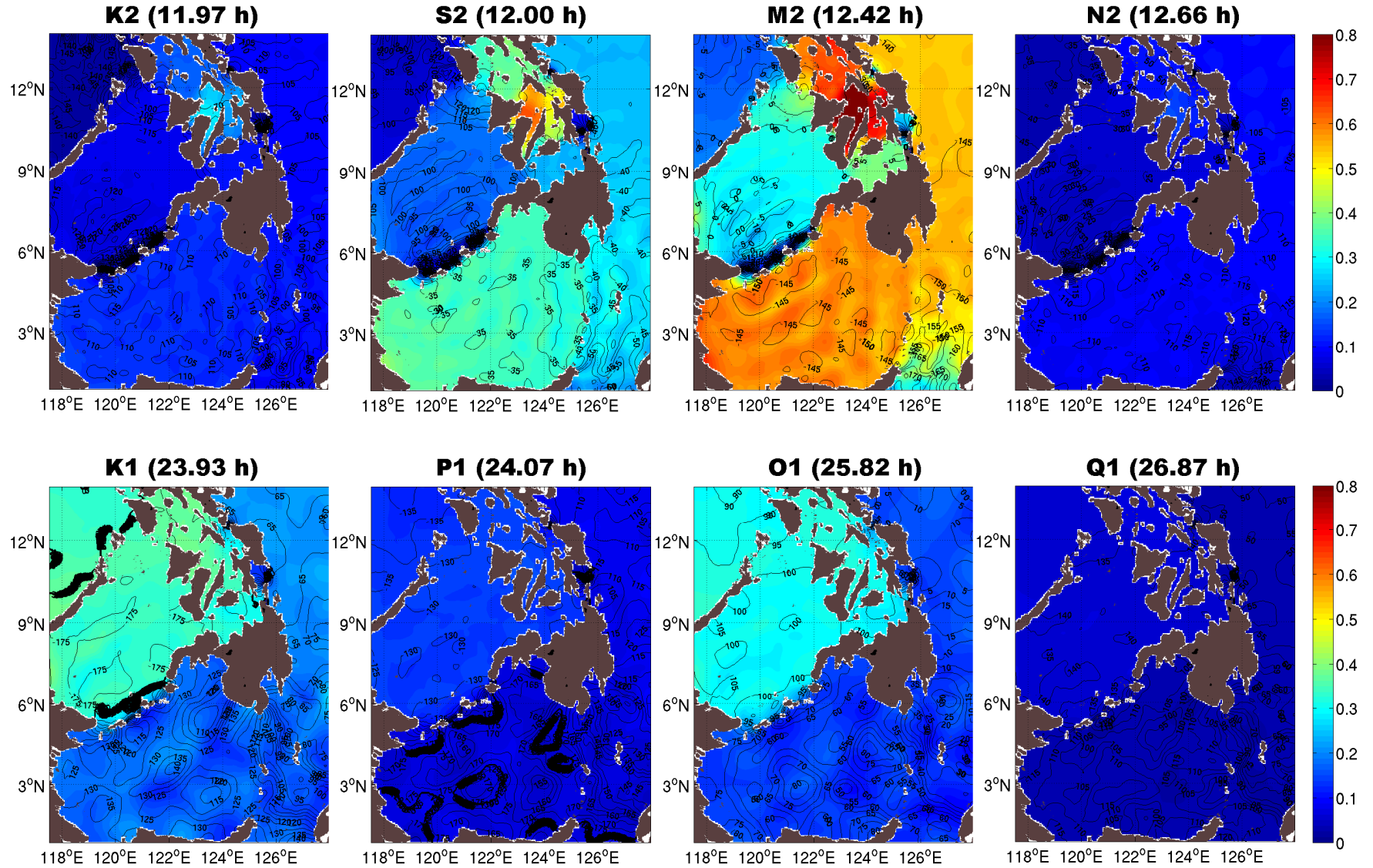


Figure 1: Tidal elevation amplitude (m; colors) and phase (degrees; contours) in the Philippine Archipelago. The panels show the harmonic decomposition of semi-diurnal (K2, S2, M2, and N2) and the diurnal components (K1, P1, O1, and Q1)

The next ROMS/TOMS [user's workshop](#) will be held at Jean Kuntzmann laboratory amphitheater, Saint Martin d'Heres Campus, Grenoble, France, October 6-8, 2008. We will also host an [Asia-Pacific Workshop](#) at the Sydney Institute of Marine Science (SIMS), Sydney, Australia, March 31 – April 2, 2009.

IMPACT/APPLICATIONS

This project will provide the ocean modeling community with a freely accessible, well-documented, open-source, terrain-following, ocean model for regional nowcasting and forecasting that includes advanced data assimilation, ensemble prediction, and analysis tools for adaptive sampling and circulation dynamics, stability, and sensitivity.

TRANSITIONS

The full transition of ROMS/TOMS to the operational community is likely to occur in the future. However, the ROMS/TOMS algorithms are now available to the developers and scientific and operational communities through the website <https://www.myroms.org>.

RELATED PROJECTS

The work reported here is related to other already funded ONR projects using ROMS. In particular, the PI (H. Arango) closely collaborates with A. Moore (adjoint-based algorithms) at University of California, Santa Cruz, A. Miller and B. Cornuelle (ROMS adjoint and variational data assimilation) at Scripps Institute of Oceanography, E. Di Lorenzo (Southern California predictability) at Georgia Institute of Oceanography, and J. Wilkin (Mid-Atlantic Bight variational data assimilation) at Rutgers University.

The PI is also supported by the following grants:

“Characterization and Modeling of the Philippine Archipelago Dynamics Using the ROMS 4DVAR Data Assimilation System”, grant number N00014-04-1-0417, <https://www.myroms.org/philex>.

“Community Sediment Transport Model”, NOPP project, award number Woods Hole A100493.

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